Reduction of the Kicker Impedance Maintaining the Performance of Present Kicker Magnet at RCS in J-PARC

Yoshihiro Shobuda (J-PARC/JAEA),
Tomohiro Takayanagi, Tomohito Togashi,
Kazami Yamamoto and Masanobu Yamamoto (J-PARC/JAEA)
Yoshiro Irie (J-PARC/KEK)

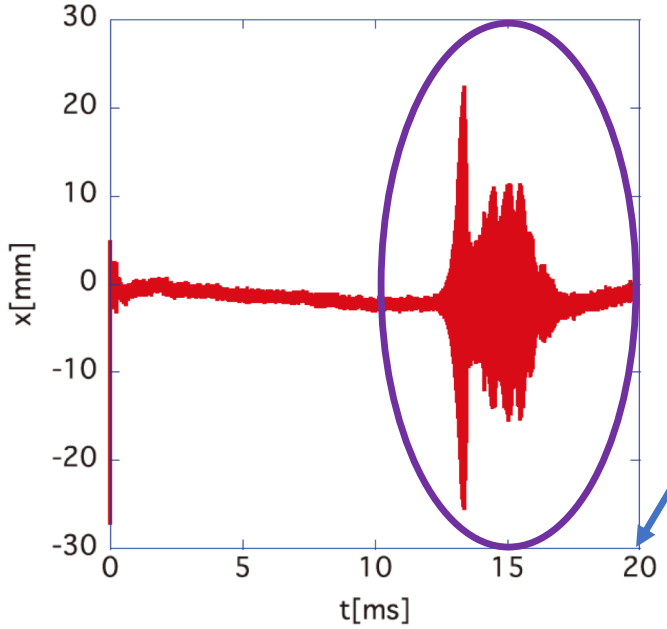
◆ Outline

- ➢ Introduction
- ➢ History
- ➢ Motivation
- ➢ Characteristic of the present kicker
- ➢ A new scheme to reduce the kicker impedance
  - ☐ Does the kicker function? (measurement vs simulation)
  - ☐ Is the impedance reduced? (measurement vs simulation)
- ➢ Summary

➢ Introduction

- The RCS at J-PARC accelerates **two** bunched proton beams during **20ms**.
- One megawatt beam is equivalent to
  the case that **$4.15*10^{13}$ ppb** are accelerated.
- The **coupled bunch instability** is observed
  at the latter half of the acceleration period (**high energy**).

Measurements for $4.15*10^{13}$ ppb (1MW-eq)

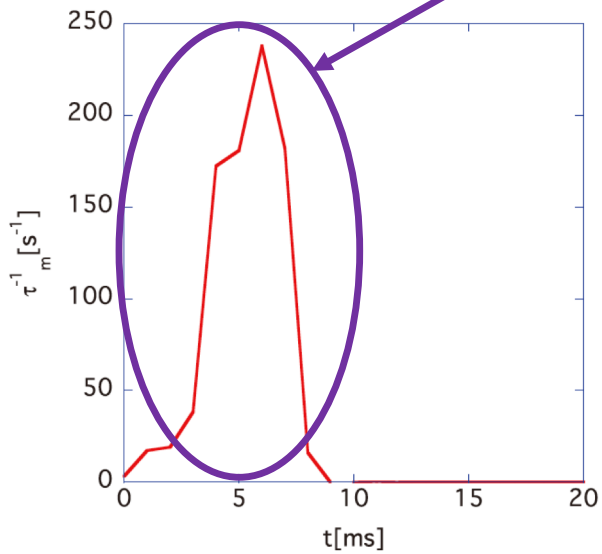


➢ History

- From the beginning, the kicker impedance was measured by **the standard wire method**.
- Since a very early stage of beam commissioning,

Sacherer's theory, where the **space charge effect is neglected**, has predicted the kicker impedance excites **beam instabilities** at low energy and **makes it impossible to realize high intensity beams** at the RCS.(*Chin et al, HB2008, p.40*)

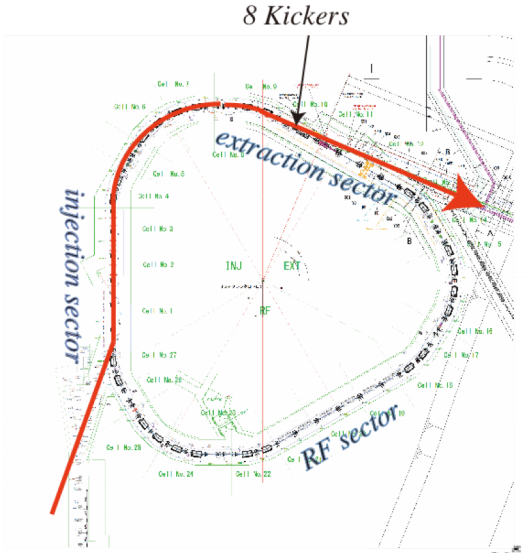
Maximum beam growth rate estimated by Sacherer's theory for 1MW beam



■ We measured the impedance by using **beams** (***Shobuda*** *et al, NIM A713, 52 ,2013)*

Measurement scheme:

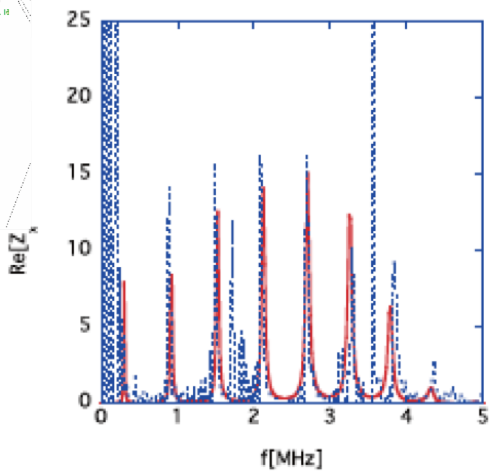
1. *Let a small injection (pulse) beam from LINAC pass through the kickers once.*
2. *Measure beam-induced voltage at ends of coax. cables, connected to the kicker.*
3. *The measured beam-induced voltage was converted to the kicker impedance.*

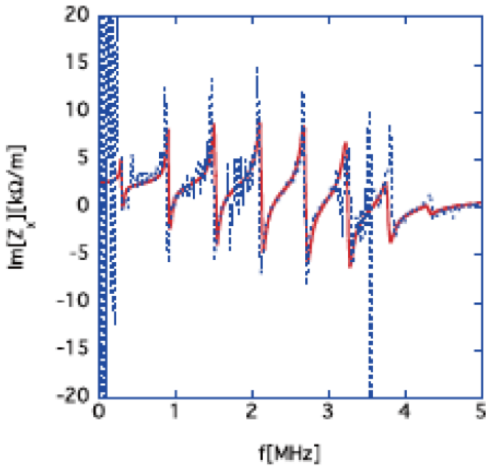


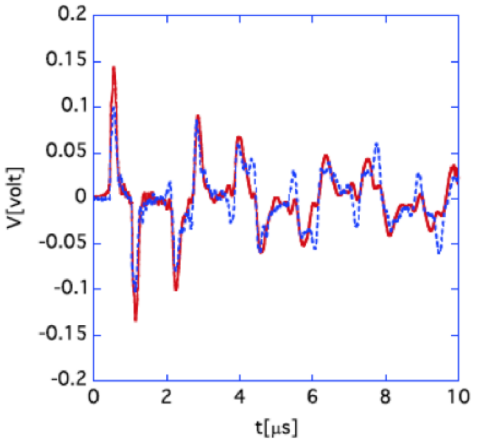
LINAC

Red: Theory
Blue: measurement

Beam-induced voltage at the end of coax. cable, connected to the kicker.





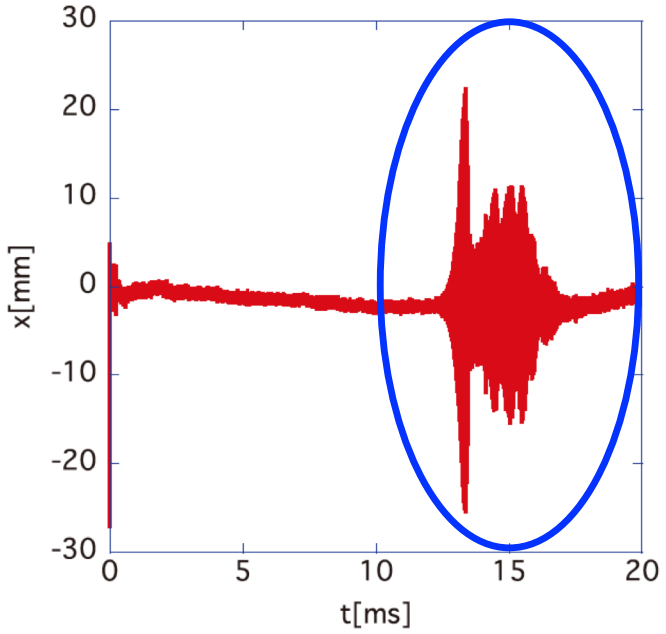


Horizontal impedance for Lorentz-β=0.55

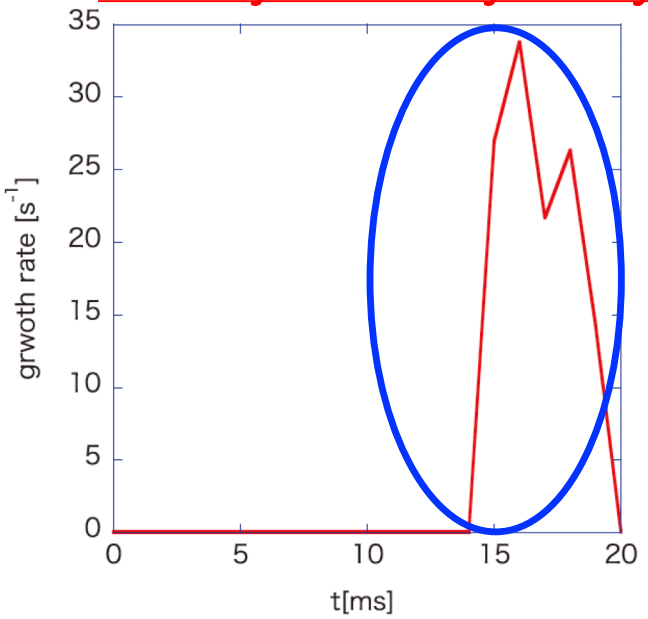
- We have **established a theory to estimate RCS kicker impedance.**
  - The theory well explains the measurement results.
  - The horizontal impedance is roughly proportional to Lorentz-β at low frequency.
- The **measurements** have demonstrated the RCS **kicker impedance** is absolutely **huge.**

- In addition, we have theoretically clarified **a mechanism for suppressing space charge effects (with chamber-wall) on the coupled-bunch instability** at the RCS.
  *(**Shobuda** et al, **P**rogress of **T**heoretical and **E**xperimental **P**hysics, 013G01, 2017)*
- The theoretical results are presently justified by simulations.
  (Saha et al, PRAB, 024203, 2018)
- We can theoretically understand **the beam instability observed at high energy.**

Measurements for $4.15*10^{13}$ ppb (1MW)



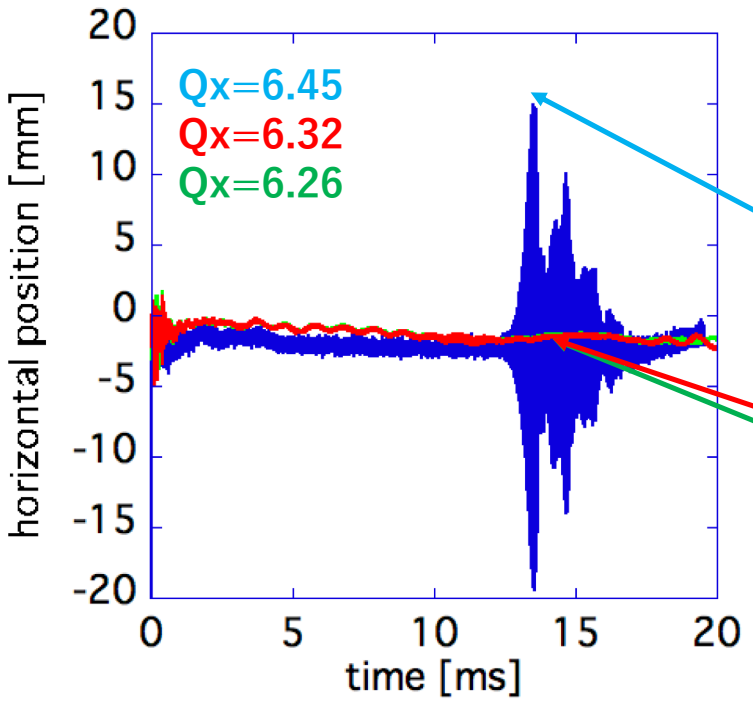
Maximum beam growth rate for 1MW beam by our theory theory



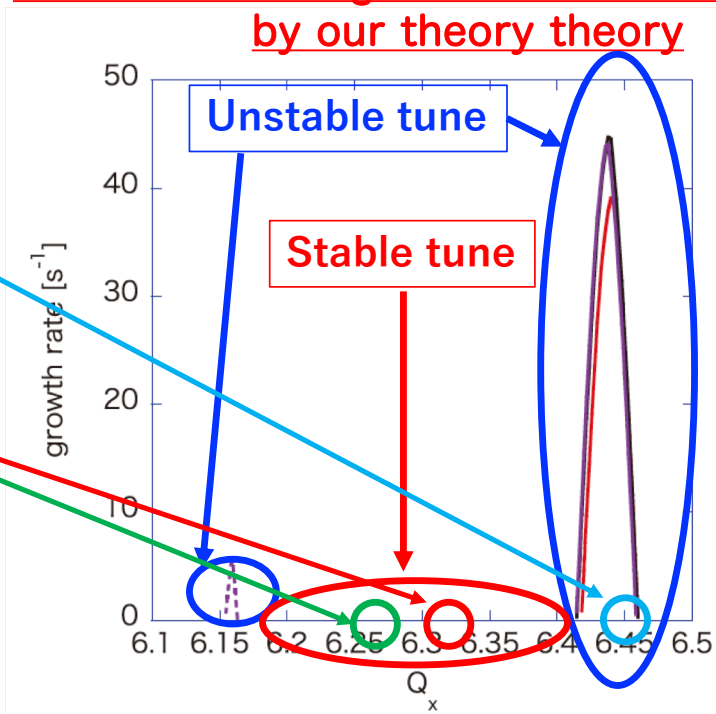
***Shobuda** et al, PTEP,013G01, (2017)*

- Moreover, we have now **demonstrated a 1-MW-equivalent beam <u>with large transverse beam emittance</u>.**
  - by manipulating the chromaticity correction pattern,
  - optimizing the tune-tracking pattern during the acceleration period.
  - This tune manipulation is important, because the beam growth rate has **tune dependence specified by the kicker impedance, as theoretically predicted**.

<u>Measurements for 4.15 *10^{13} ppb (1MW)</u>



<u>Maximum beam growth rate for 1MW beam by our theory theory</u>



***Shobuda** et al, PTEP,013G01, (2017)*

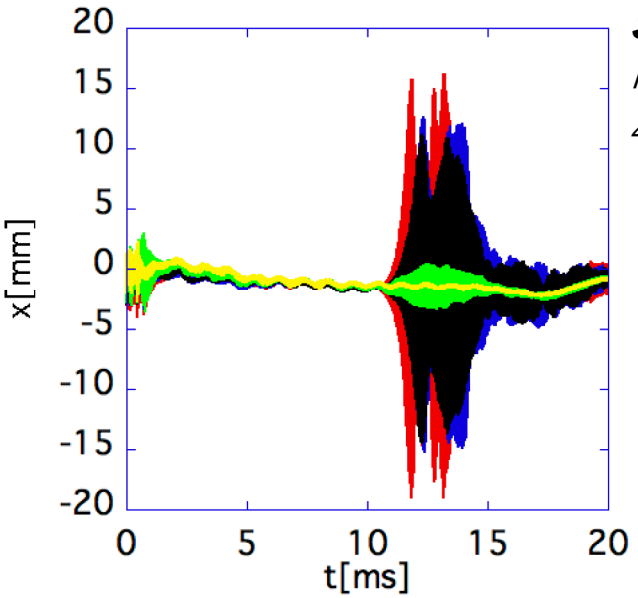
➢ Motivation

- Nevertheless, we should better reduce the kicker impedance toward routine high intensity beam operations, especially for the smaller transverse emittance beam.
- Because the beam with smaller emittance theoretically tends to be unstable at high energy.
- We have observed the phenomena in the measurements, as well.

Measurements of the transverse emittance dependence of beam growth rate for 910kW beam

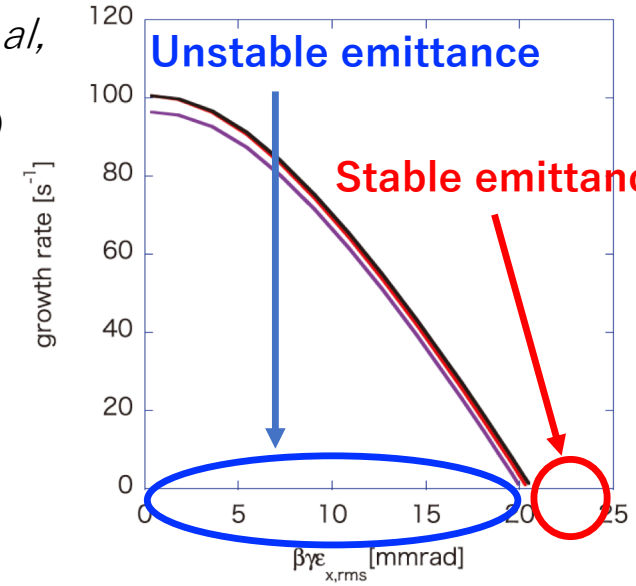
The painting emittance:

- 50 π injection
- 75 π injection
- 100 π injection
- 150 π injection
- 200 π injection



***Shobuda** et al, IPAC2017, 2946, (2017)*

Theoretical results showing the emittance dependence of beam growth rate for 1MW beam



***Shobuda** et al, PTEP,013G01, (2017)*

- The small emittance beam is inevitable at the RCS,
  because it is going to be delivered to the Main Ring at J-PARC.

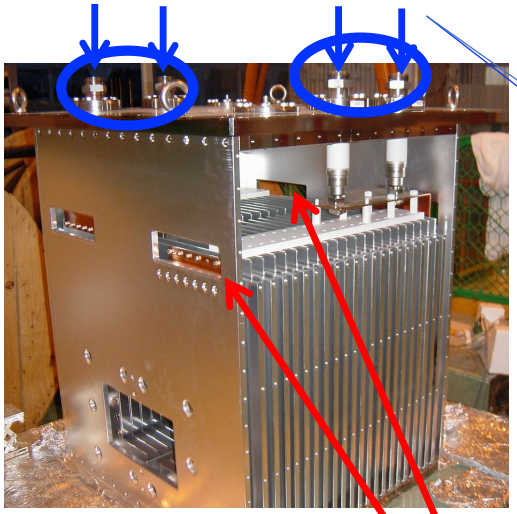
- Typically, a special tune manipulation let the small emittance beam escape the resonance lines excited by the magnet errors at the RCS.

- On the other hand, possible tune tracking patterns are restricted for the small emittance beam,
  because the beam can be more unstable due to the kicker impedance.

- That is why,
  we need to widen the allowable region in the tune diagram for the small emittance beam by suppressing the kicker impedance.

➢ The characteristic of the present RCS kicker

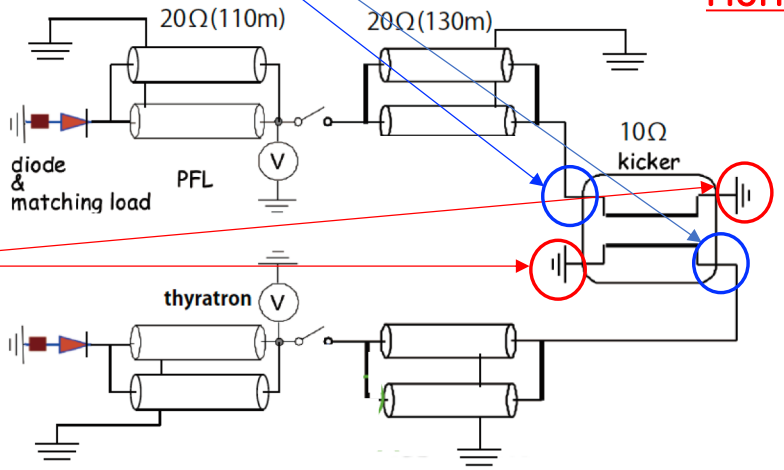
Inputs for 130m coaxial cables



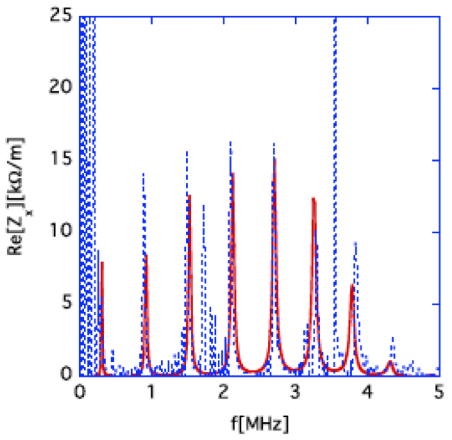
Kicker magnet

- The kicker magnet at the RCS has four terminals.
- Two are connected to Pulse Forming Line (PFL), while the others are terminated by **the short plates**.
- **The short plates generate a power saving benefit** by doubling the excitation current by superposing the forward and backward currents, when a beam is extracted from the RCS.

Short plates



Horizontal impedance at β=0.55



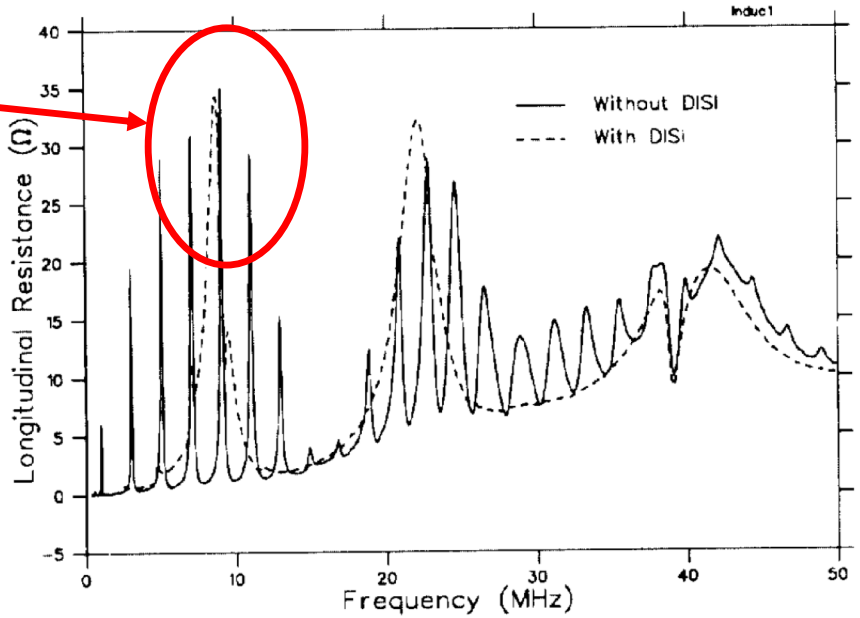
- On the other hand, **the short plates create the resonance structure** in the kicker impedance in combination with the coaxial cables.

- In 1993, TRIUMF aimed at reducing the impedance of kicker, terminated with **shorted-circuit** by inserting a saturating inductor between the magnet end and the cable terminals *(Tran et al, PAC93, 3502).*

- When a beam is accelerated, since the device effectively terminates the cable as an open-circuit, TRIUMF successfully eliminated the resonances due to the coaxial cables from the impedance (**solid line → dashed line**).

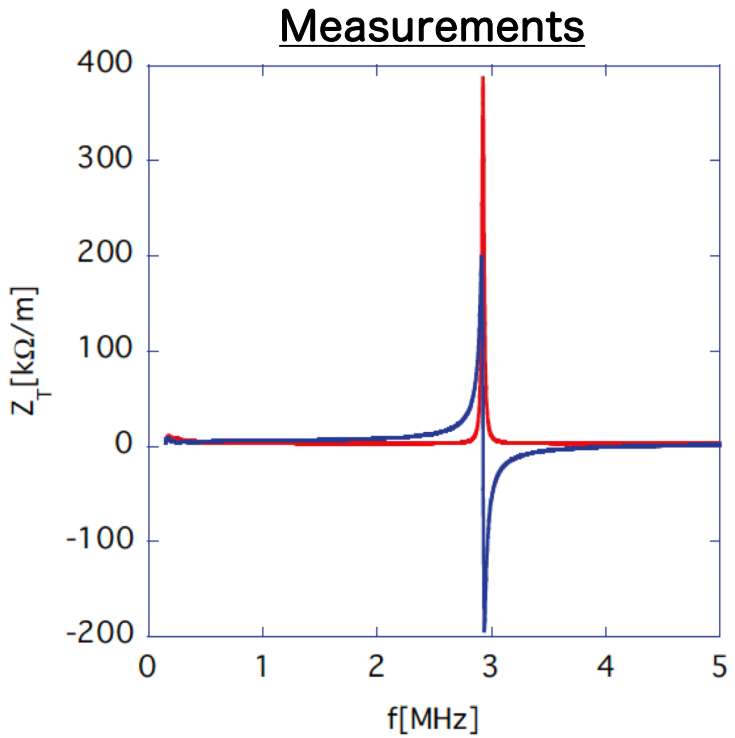
- Unfortunately, the maximum value of the impedance remains the same order of magnitude.

Tran et al, PAC93, 3502



- In order to simulate the RCS kicker with the saturating inductor, we measured the kicker impedance, after detaching all coaxial cables from the RCS kicker (the terminals are completely open).

- Finally, the measurements demonstrate a huge impedance enhancement, though the resonance structure diminishes.

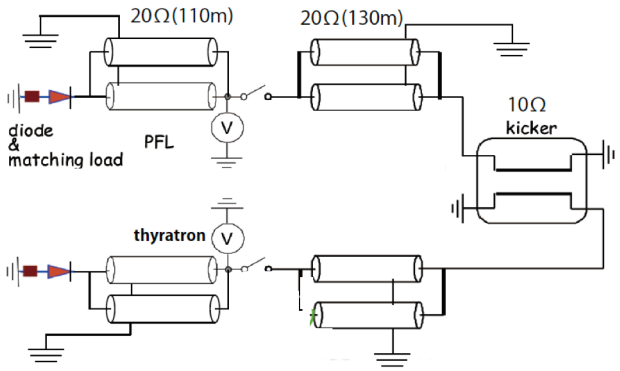


Red : real part
Blue: imaginary part

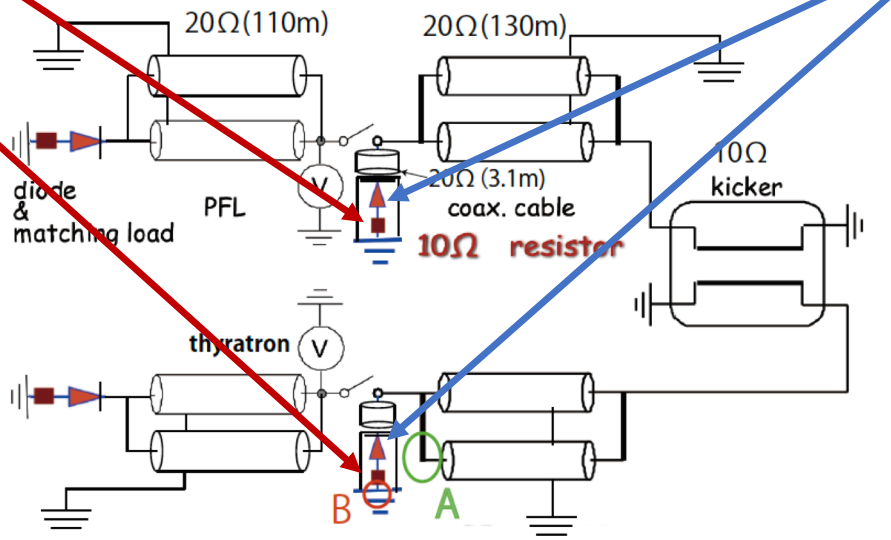
➢ A new scheme to reduce the kicker impedance

- ◆ In order to reduce the impedance, one possible solution is inserting **a resistor** between the coaxial cable and PFN.
  - ●Notice that we must retain the benefit of short plates.
  - ●Thus, the resistor has to be isolated from the PFN, but needs to be seen by a beam.
  - ●We need a mechanism to isolate the damping resistor from the pulse current from the PFN.
  - ●From a mechanical point of view, the easiest way is to insert a **diode** in front of the resistor.

present



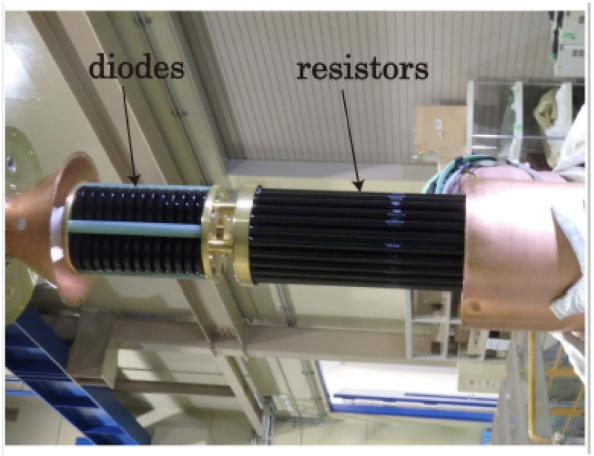
Modified



■ Practically, the diode must have the higher reverse voltage V_R and the lower forward voltage V_F.

- The requirement to the actual diode at the RCS kicker:
  - ✓ the reverse voltage V_R must have at least 40kV or higher, to block DC current,
  - ✓ the forward voltage V_F should be 50 V or lower, to let a beam current see the resistor.
- Based on SPICE simulation, the diode was specifically developed by ORIGIN.

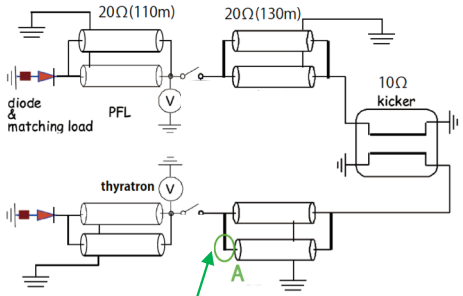
Diode unit
(diode+resistors)



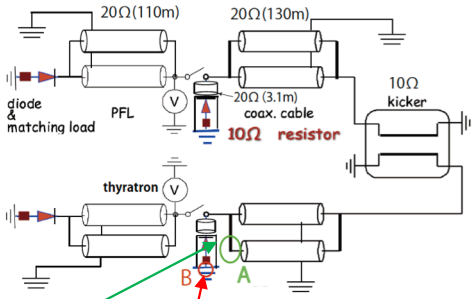
■ Now, let us experimentally confirm

- whether the durability of diode is sufficient (**the kicker functions**) when the pulse current flows for the beam extraction.
- whether the beam-induced current flows the diode **(the impedance is reduced).**

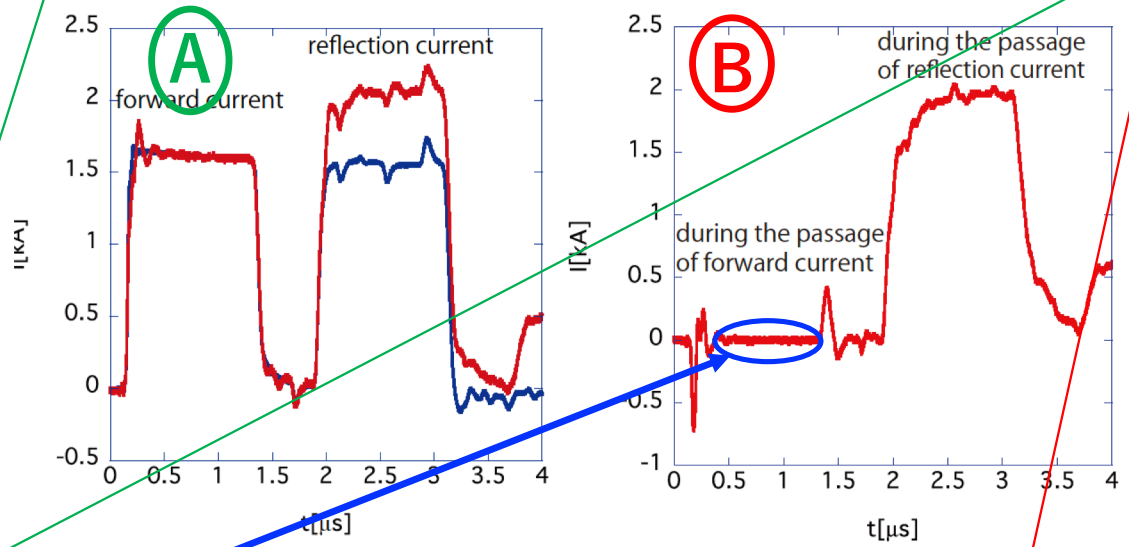
Present kicker (without diode unit)



Modified kicker (with the diode unit)

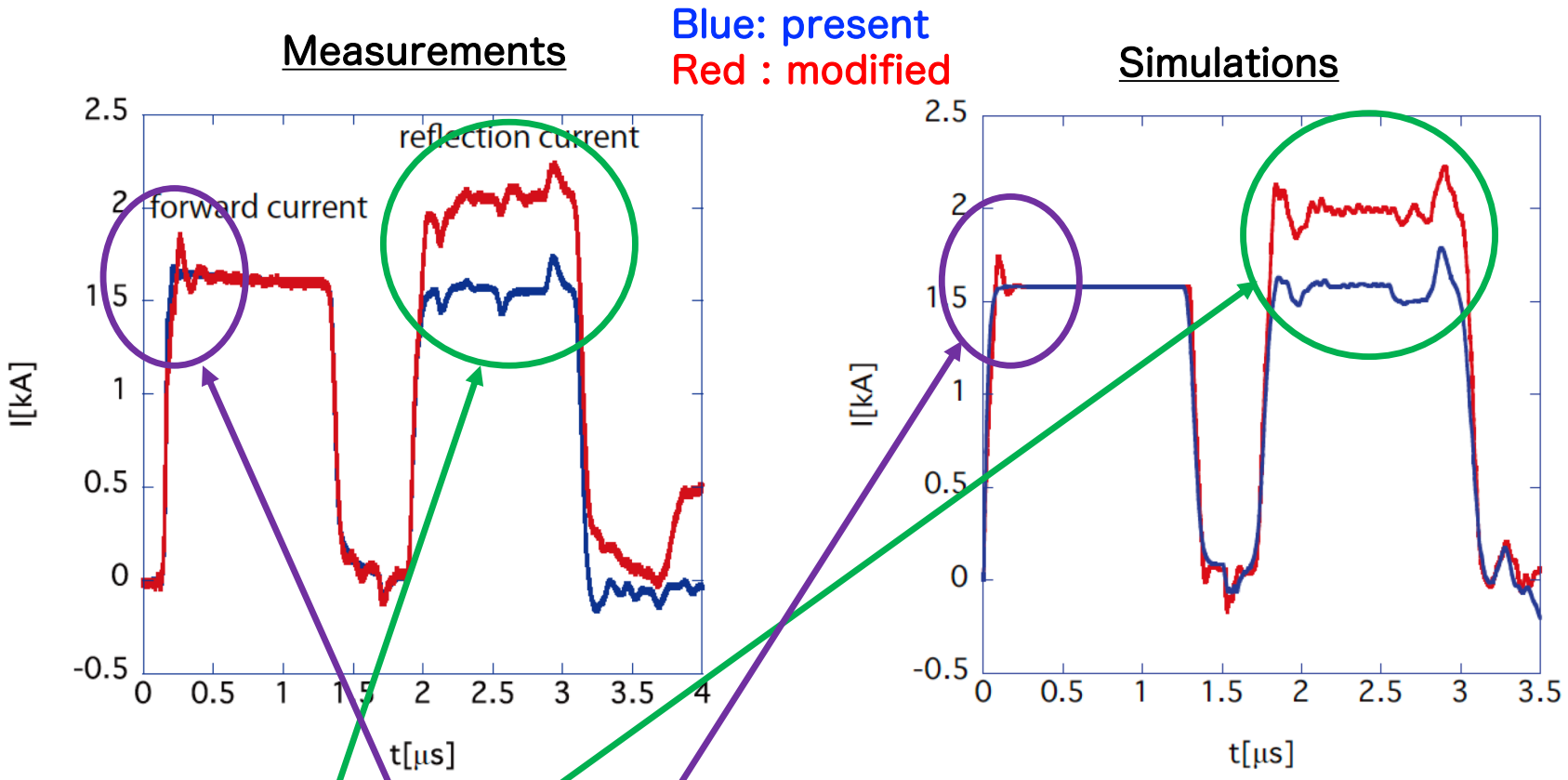


measurements



Blue: present
Red : modified

- Firstly, switch on the PFN, then, measure both the current on the **cable** at the position **A** and the current on the **diode** at the position **B.**
- The **diode is sufficiently durable,** because **no current flows** on the diode (**B**) during the passage of forward current except the rising and falling periods.

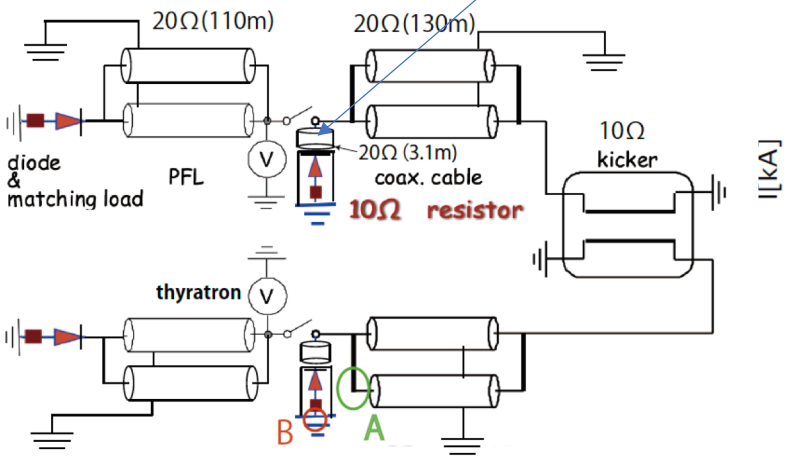


- The measurements at position **A** (cable) are well reproduced by simulations.
- The diode unit violates the matching condition for the reflection current, which **enhances the red current** compared to **the current** on the present kicker.
- One can see the **oscillation** during the rising edge for both results.

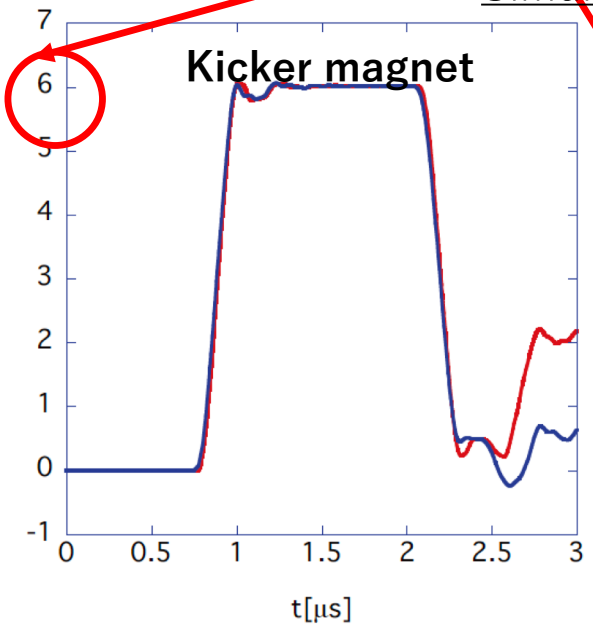
- This is due to the present measurement set-up, mainly due to 3.1 m coaxial cables, connecting the diode unit to the ends of 130 m cables.
- Practically, we can eliminate the oscillation by shorting the length to 1m or less.

Conclusions about the pulse current from PFN,

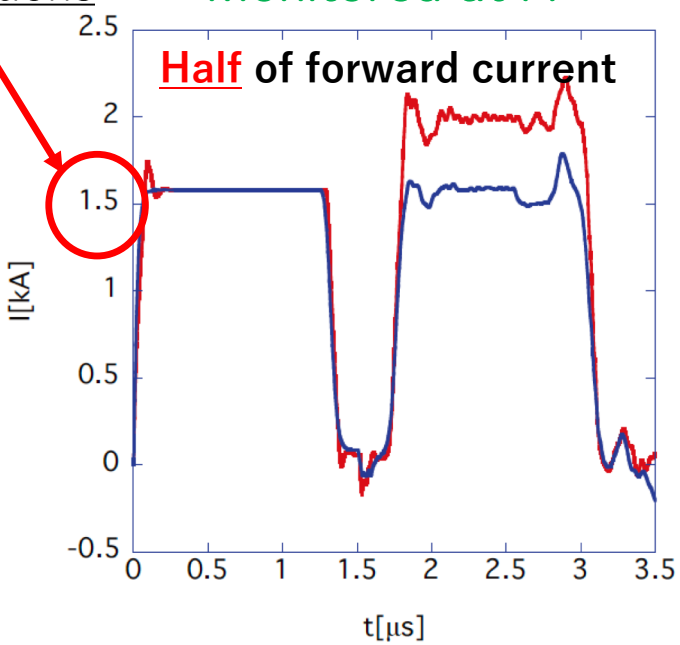
1. **The diode is durable.** The measurement is well reproduced by simulations
2. The simulation suggests
   the original forward current is successfully **doubled** at the kicker magnet.



Simulations



Monitored at A



◻ *The reduction of the kicker impedance (I) (by measurement approach)*

- Conventionally, the kicker impedance is measured with the standard wire-method by stretching wires inside the kicker,
  - ✓ First, measure the scattering matrix.
  - ✓ Then, convert it into the impedance.

- **The method cannot measure the impedance** of the kicker with the diodes, because the measurement is done in **frequency domain** by using **weak currents** with Network Analyzer.

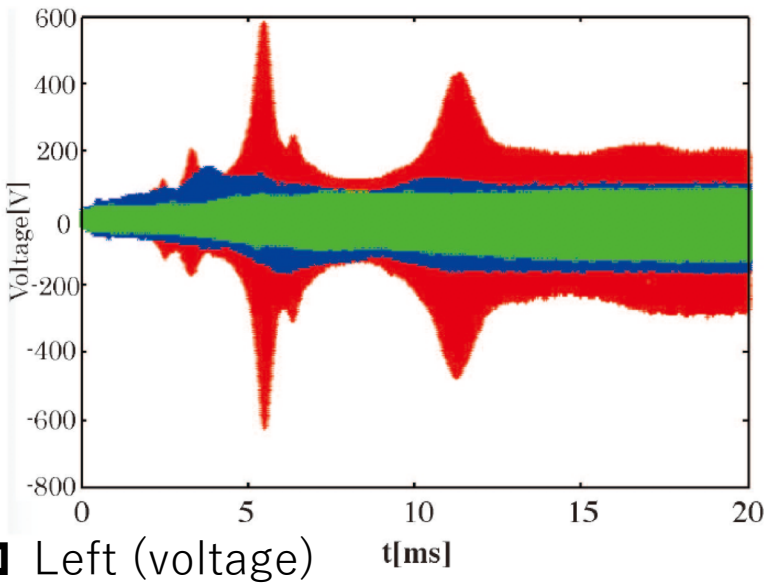
■ The kicker impedance must be measured **in time domain** by the **high intensity beam** at the RCS.

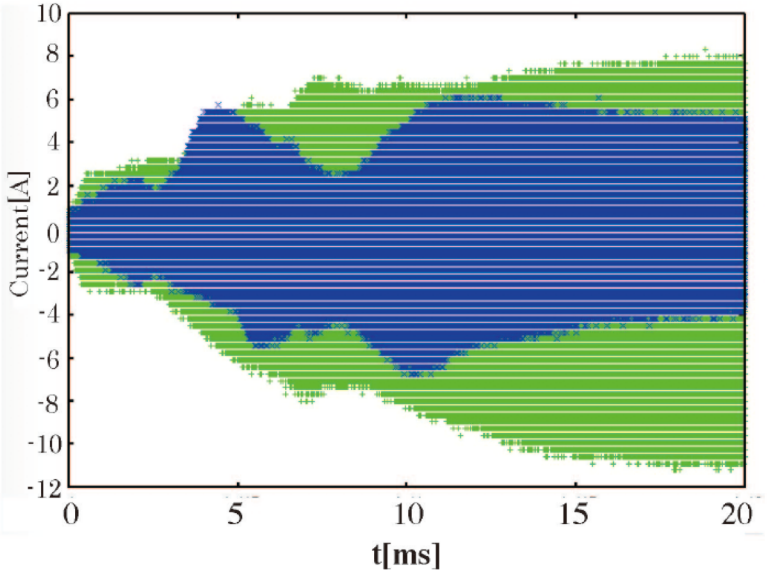
- The kicker impedance is related to the beam-induced voltage and currents at the ends of the coaxial cables *(**Shobuda** et al, NIM A713, 52 ,2013)* .

1. Measure the voltage and current, to determine the effective terminal impedance of the diode and resistors.
2. Convert the terminal impedance to the kicker impedance.

■ Let us measure the beam-induced voltage and current during the acceleration.

(1) Measurements when a beam with 3.11*10^{13} (750 kW-eq) ppb passes through the kicker.





Red: open
Blue: diode with resistor
Green: 10 ohm resistor only.

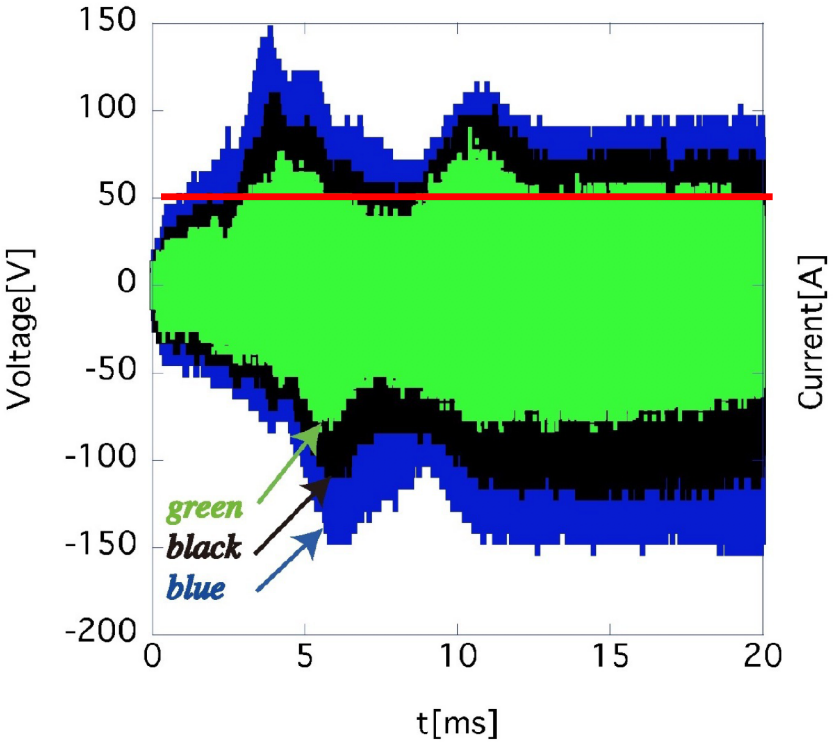
□ Left (voltage)

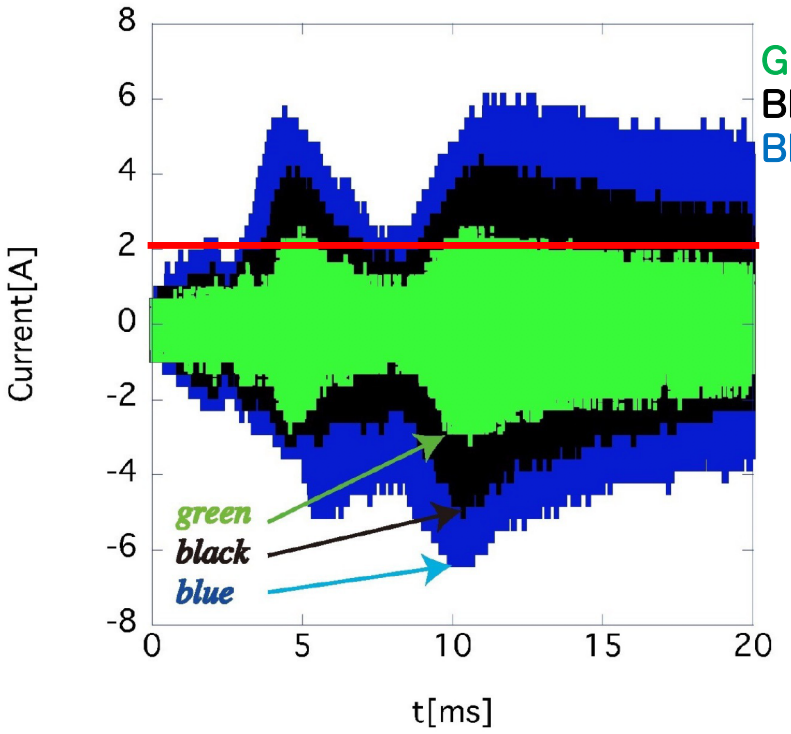
(1) **When only the matched resistors are connected**, the voltage is absorbed into the resistor.
(2) **When the terminals are open**, the voltages are superposed, and they become maximum.
(3) **When the diodes are inserted in front of the resistors,** the voltages lie between **the red** and **the green** because the matching conditions are not perfectly satisfied.

□ Right (current)

(1) **The current for the diode with resistors** is lower than **that for the matched resistor.**
(2) **The current decrease** reflects the kicker impedance enhancement, due to the additional diode's resistance.

(2)The beam-intensity dependence of the beam-induced voltages and currents



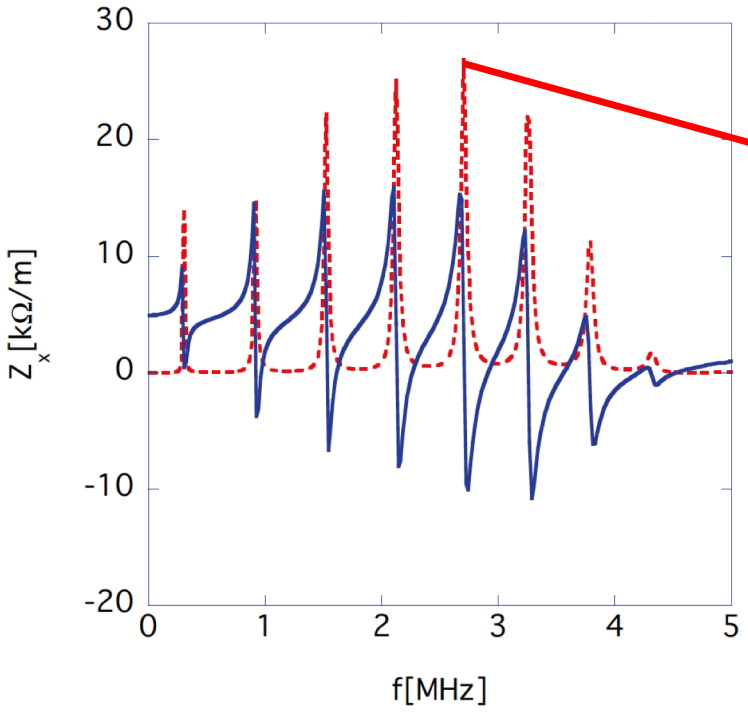


Green: $1.245*10^{13}$ (300kW-eq)
Black: $2.075*10^{13}$(500kW-eq)
Blue: $3.11*10^{13}$ (750kW-eq)

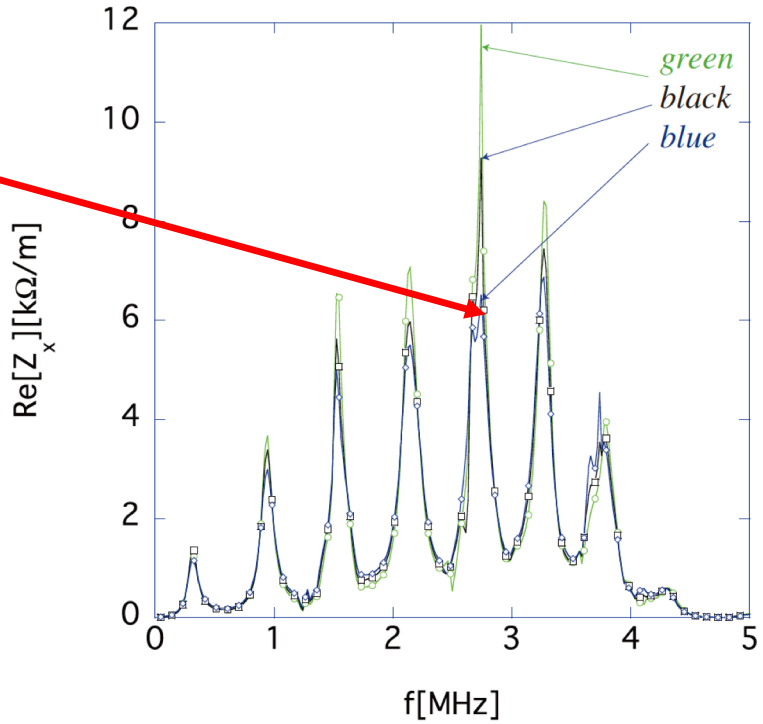
- As the beam-intensity increases, the beam-induced voltages increase (left).
- The beam-induced currents (right) increase more than the beam-induced voltages (left) as the beam intensity increases.
  - The kicker impedances with the diodes and resistors are reduced more as the beam intensity increases.
- This is because V-I curve of diode rises rapidly (dynamic resistance reduction) as the V increases.

◆ *Summary of the beam-intensity dependence of the measured kicker impedance at 3GeV.*

Analytical result of horizontal impedance of the present kicker for a relativistic beam



Measurements of horizontal impedance of the modified kicker at 3GeV



Green: 300kW-eq
Black: 500kW-eq
Blue: 750kW-eq

- The scheme successfully makes the present kicker impedance halved or less.
- The diode becomes more conductive for higher beam induced-current.
- Accordingly, the impedance is reduced, because the terminal impedance (diode+resistor) approaches the characteristic impedance of the kicker.

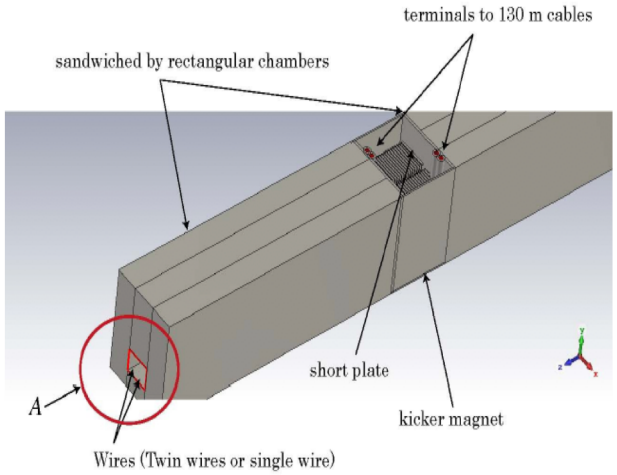
☐ *Reduction of the kicker impedance (II) (by simulation approach)*

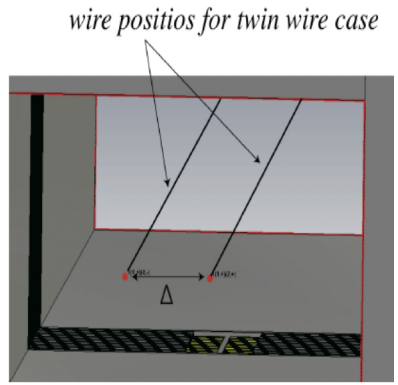
■ The **Wake Solver** of CST is one of world wide tools to simulate the beam-impedance by exciting wake fields in the device under test **with a beam**.

Main difficulty:

● The Wake Solver cannot be utilized at the RCS
- ☐ Because 130-m-long cables are connected to the kicker,
- ☐ Excessive memory and CPU time are necessary.

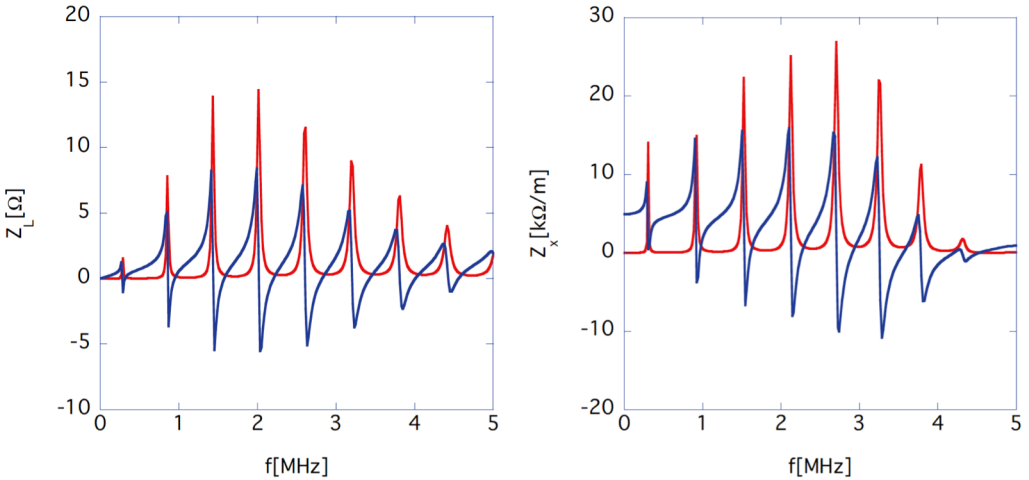
Solution:
- ☐ Simulate the measurement setup of the wire method, by assuming the method well reproduces the impedance excited by a beam.
- ☐ This assumption is applicable to the RCS kicker. (***Shobuda*** *et al, NIM A713, 52 ,2013*).
- ☐ We make use of the **MicroWave Solver**, bypassing the Wake Solver.
- ☐ In this scheme, 130-m-long cables and diodes can be easily incorporated into the simulation.



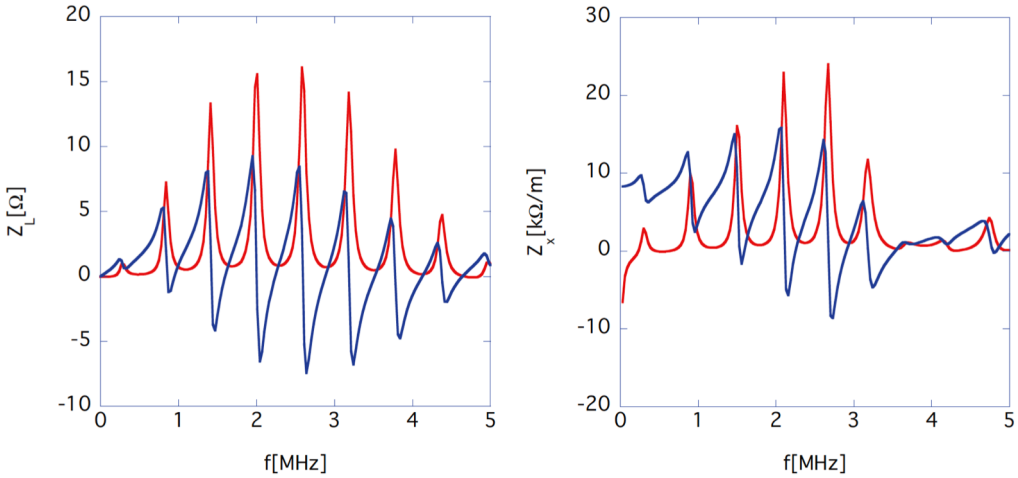


(1) Analytical and simulation results for the present kicker

Analytical result for a relativistic beam (with dispersion relation of cable)



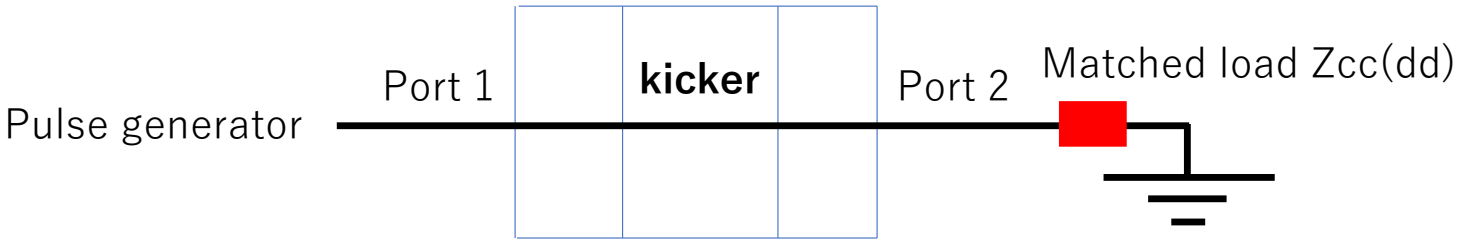
Simulation for a relativistic beam (No dispersion relation of cable)



- This simulation result well explains the analytical result.
  - A discrepancy can be still seen, which is caused by the dispersion relation of 130 m cable.
  - This is a present limit of the simulation approach by using CST code, because the present CST cannot incorporate the dispersion relation of the cable.

(2) Simulate the impedance of kicker with diodes and resistors.

- Typical approach **in frequency domain**
  cannot be applicable to the estimate of the scattering matrix (which is converted to the impedance) of the modified kicker, because the nonlinear device (diode) exists in the kicker.
- Firstly, simulate the voltages and currents **in time domain**,
- Then, they must be transformed into those in frequency domain.
- Finally, we can determine the beam intensity dependence of the kicker impedance.

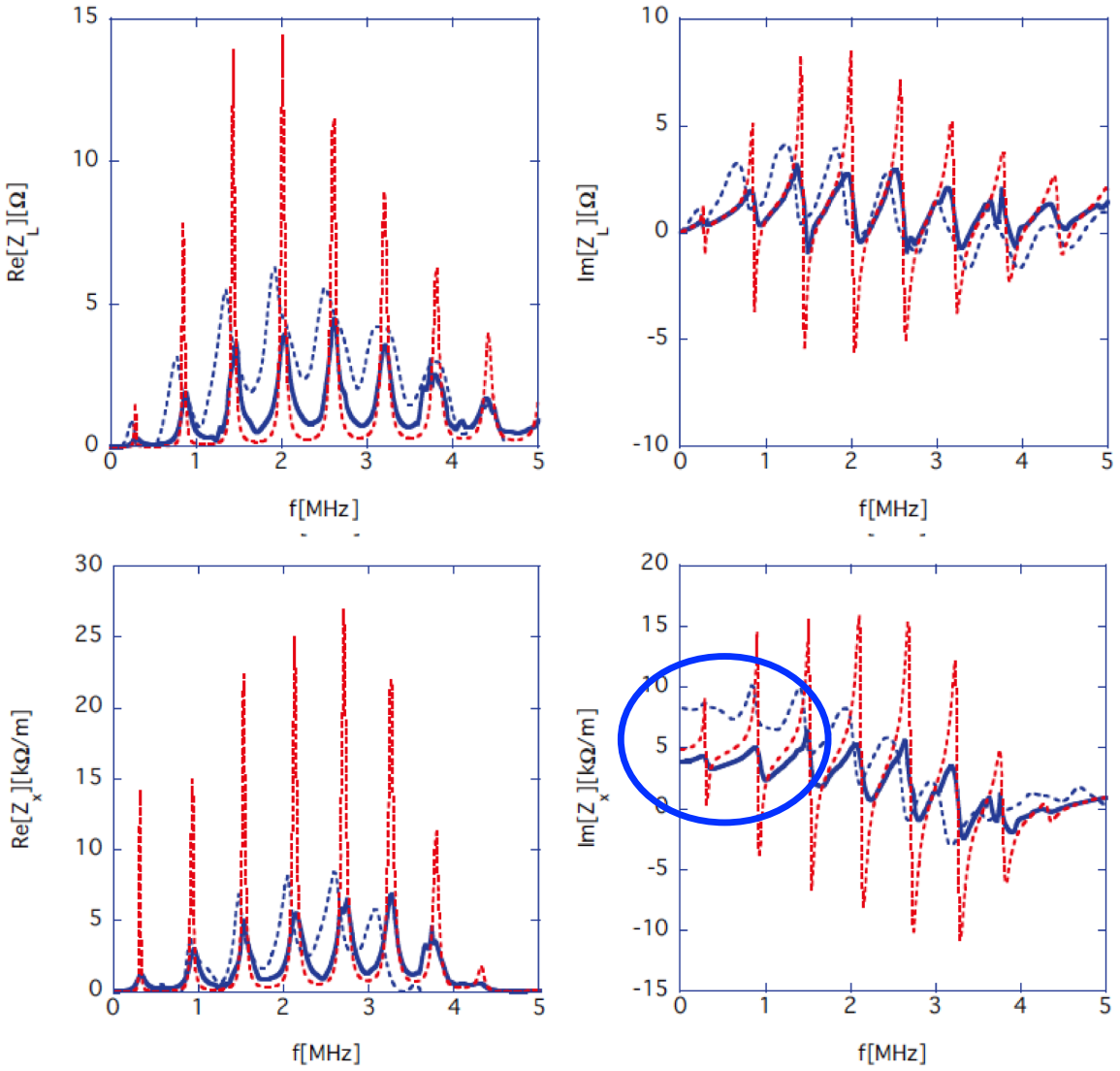


$$S_{cc(dd)21} = -\frac{2Z_{cc(dd)}\tilde{I}_2}{\tilde{V}_1 + Z_{cc(dd)}\tilde{I}_1},$$

$$Z_L = -2Z_{cc}\log\frac{S_{cc21}^{DUT}}{S_{cc21}^{(ref)}},$$

$$Z_x = -\frac{2cZ_{dd}}{\omega\Delta^2}\log\frac{S_{dd21}^{DUT}}{S_{dd21}^{(ref)}},$$

◆ *Summary of the simulated and measured impedance of the modified kicker for a relativistic beam.*



Red: Analytical result of present kicker

Blue dashed: Simulated result of 750 kW beam for modified kicker

Blue solid: Measured result of 750 kW beam for modified kicker

- The scheme significantly reduces the impedance of present kicker.
- The simulation results relatively well explain the measurement results.
- The discrepancy at low frequency is due to no dispersion relation of the cable.

➢ Summary

- We have proposed a new scheme to reduce the impedance of kicker, whose terminals are shorted, to double the pulse current from the PFL.
  - The diode unit (diodes and resistors) is inserted between the ends of the coaxial cables and the PFL.
  - The unit ensures the doubled excitation currents for beam extraction by superposing the forward and reflection currents, reducing the kicker impedance.
- By using high intensity beams, we demonstrated the reduction of kicker impedance.
- We have developed a new simulation technique to estimate the impedance of kicker, connecting to long coaxial cables and nonlinear devices (diodes).
  - Utilizing the Microwave Solve of CST, bypassing the Wake Solver, is a key for the simulation.
- Since the agreement between the simulation and measurements is relatively good, the simulation technique can be a nice guideline to estimate the impedance of such kickers.